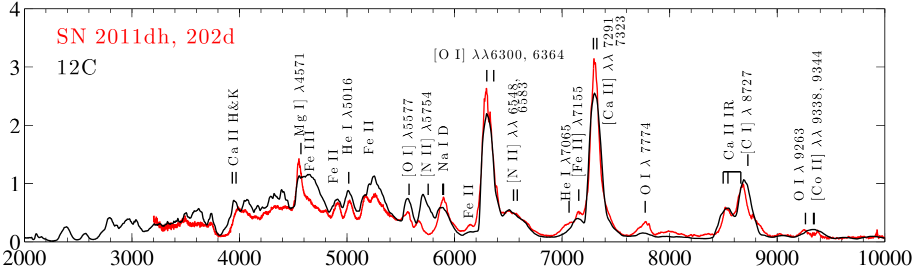
Modelling nebular-phase stripped-envelope supernovae with SUMO

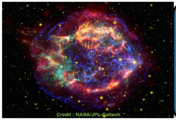
Anders Jerkstrand

Stockholm University

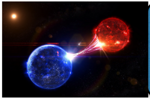


Why study supernova light curves and spectra?

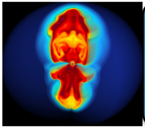
SN LCs & spectra



1) Diagnose nucleosynthesis and inner composition of stars

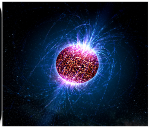


2) Diagnose and test stellar evolution

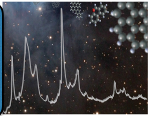


3) Understand explosive burning and the SN explosion mechanism

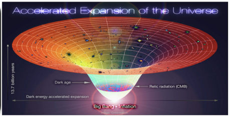
4) Constrain properties of newly formed neutron stars and black holes



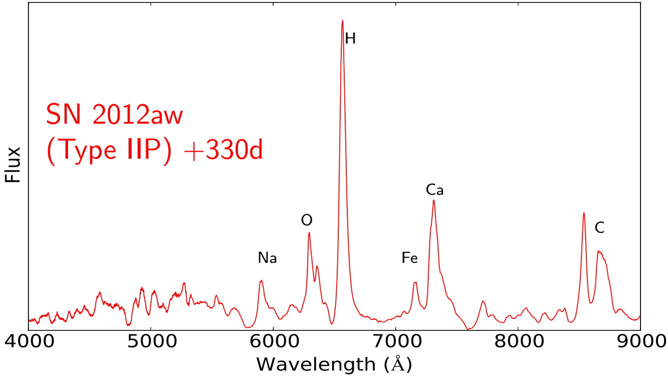
5) Probes of astrochemistry: molecule and dust formation



6) Improve use as distance indicators and cosmological probes



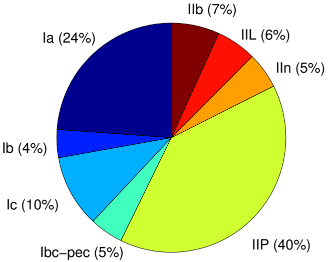
Late-phase spectra ($t \gtrsim 100$d)



- Whole ejecta creates spectrum : can see each layer in the SN
- Emission lines → direct measure of abundances
- Still complex line formation process → need NLTE radiative transfer models

Stripped-envelope supernovae : about 1 in 4 explosions

IIb : He left, some H ($\sim 0.1\ M_{\odot}$)
Ib : He left, no H
Ic : no He, no H

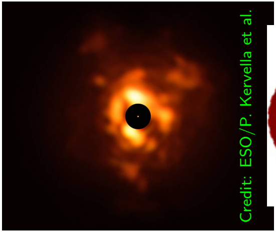


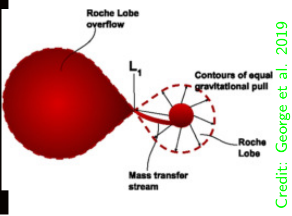
Volume-limited

Data from Li+2011

Stripped-envelope SNe : Questions where nebular modelling can help

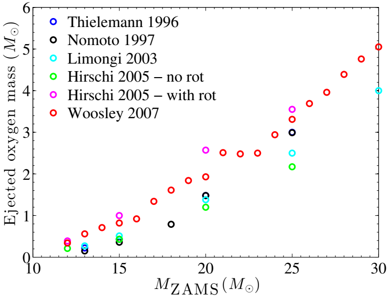
- What are the progenitors (M_{ZAMS}, Z, Ω, B, binarity) and what is the cause of the mass loss?



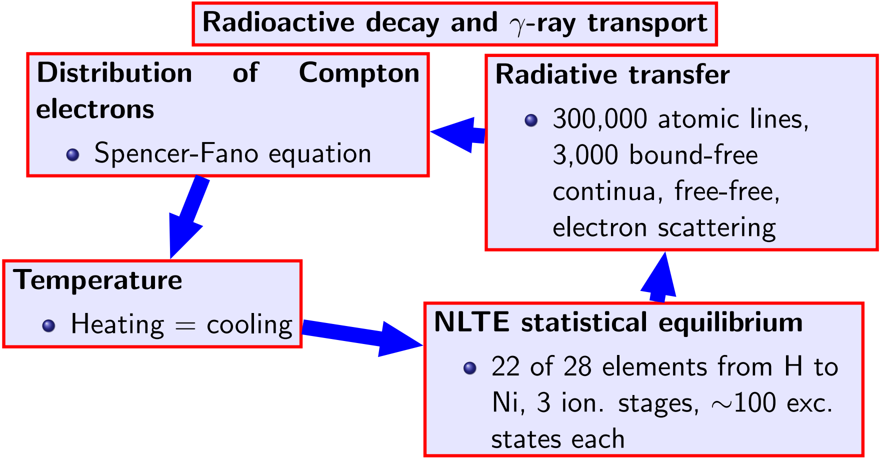


- How does the explosion occur?

- What is their contribution to galactic element production?



The SUMO code : nebular phase spectral modelling with 5 blocks of coupled physics



Jerkstrand 2011, PhD thesis, Jerkstrand+2011,2012

- Code is 1D but allows for macroscopic mixing and clumping by 'virtual grid' option.

Models available

star.pst.qub.ac.uk/wiki/users/ajerkstrand/start.html

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matter, and where the r-process elements such as gold come from.

A list of other projects Ive been involved in (various topics including CSM emission line modelling, nuclear burning simulations, atomic data, SN 1987A) can be found here.

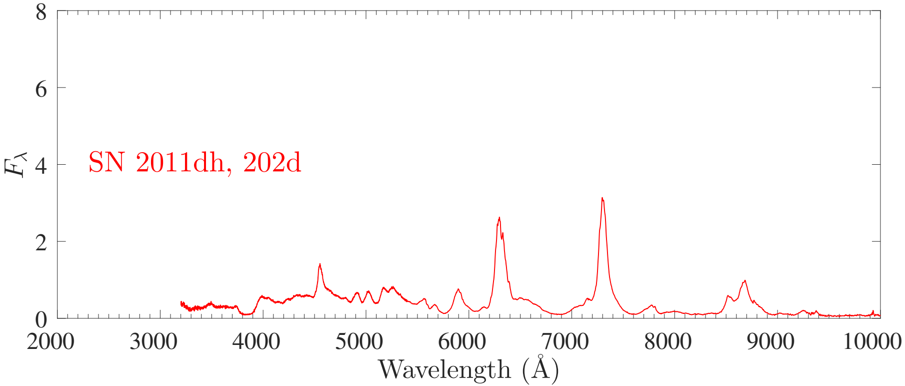
Published Models

- SN 1987A model spectra
- Type IIP model spectra
- Type IIb/Ib model spectra
- Type Ia model spectra
- Pair-instability model spectra
- SL Type Ic model spectra (single zone)
- Light curve models for super-luminous SNe
- Nucleosynthesis simulations

Developed semi-analytic methods

- 56Ni-bubble diagnostic from [Ni II] 6.63 mu, [Co II] 10.52 mu, [Fe II] 26 mu lines
- O mass from [O I] 6300, 6364 and [O] 5577 in Type II SNe
- O mass from [O I] 6300, 6364 and [O] 5577 in stripped-envelope SNe
- Ni/Fe ratio from [Ni II] 7378 and [Fe II] 7155
- The Mg mass from Mg I 1.50 mu and O I 7774, 9263, 1.13 mu, 1.31 mu lines
- The Fe mass (and thereby a constraint on the 56Ni mass) from [Fe II] 7155 and [Fe II] 1.26 mu in strippe-envelope SNe
- Constraints on T, ne, n_CaII from [Ca II] 7291,7323 and Ca Ii triplet

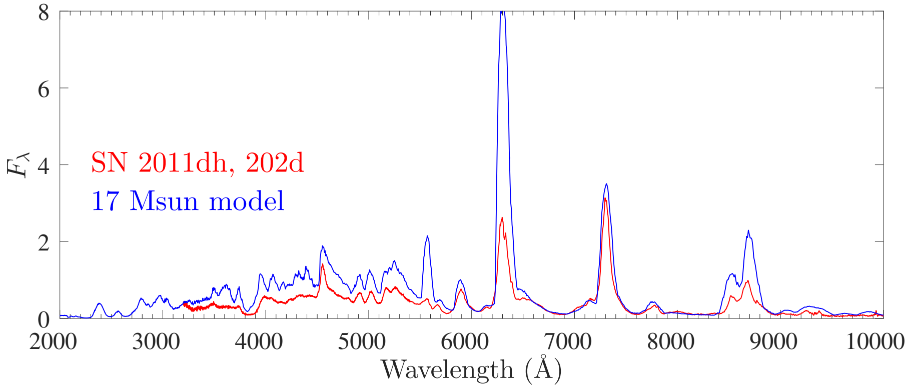
Case study : SN 2011dh (Type IIb) - best-observed stripped-envelope SN since 1993J



Jerkstrand+2015, A&A

A $M_{\mathrm{ZAMS}} = 17\ M_{\odot}$ model : too much O

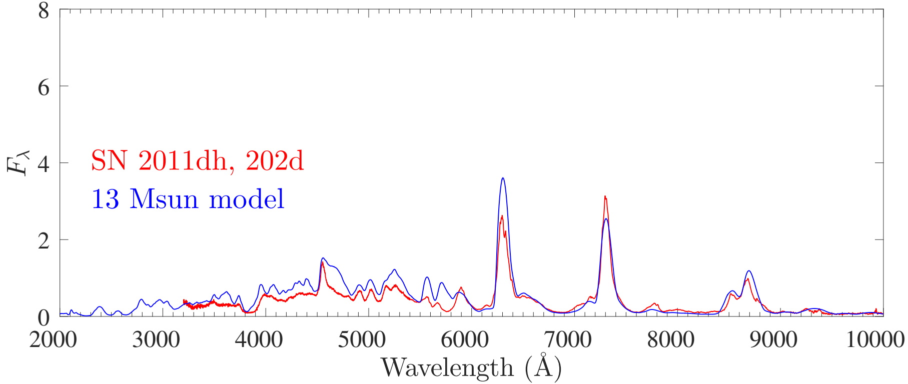
Stars evolved and exploded with KEPLER



Jerkstrand+2015, A&A

A $M_{\mathrm{ZAMS}} = 13\ M_\odot$ model : somewhat too much O

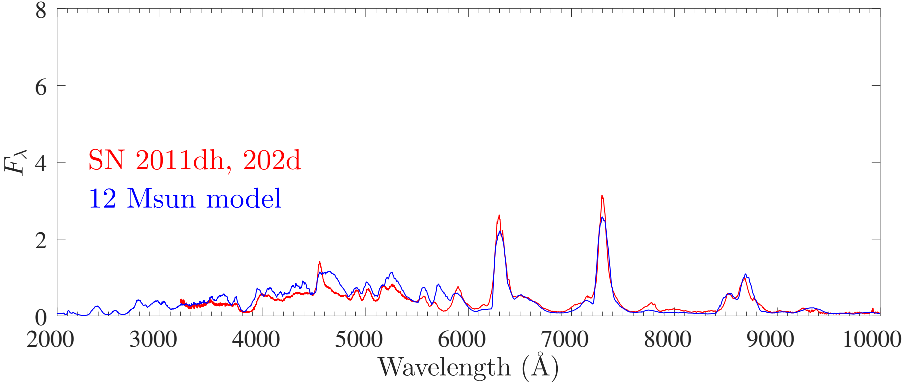
Stars evolved and exploded with KEPLER



Jerkstrand+2015, A&A

A $M_{\rm ZAMS} = 12\ M_\odot$ model : good fit throughout

Stars evolved and exploded with KEPLER



Jerkstrand+2015, A&A

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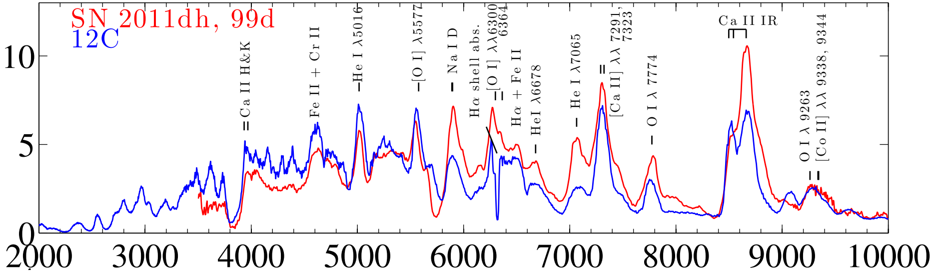
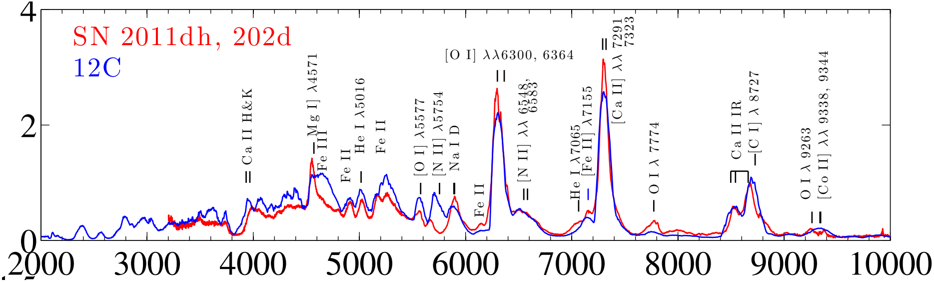
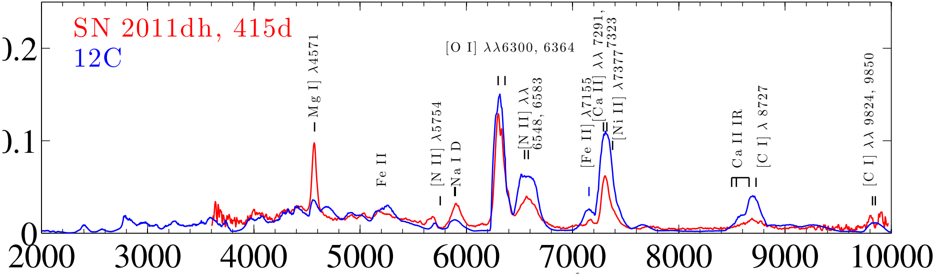
SN 2011dh : Time evolution *Jerkstrand+2015, A&A*



SN 2011dh : Time evolution *Jerkstrand+2015, A&A*

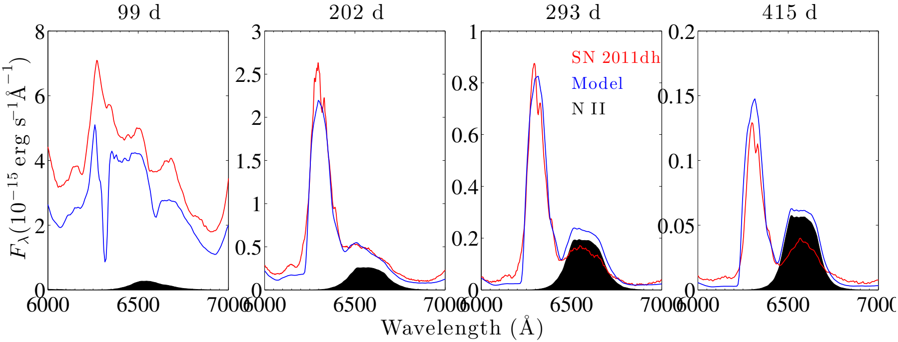


SN 2011dh : Time evolution *Jerkstrand+2015, A&A*



[N II] $\lambda\lambda$ 6548, 6583 or Hα?

- The [N II] $\lambda\lambda$ 6548, 6583 doublet is the main cooler of the He/N layer.
- The models, dominated by [N II], closely reproduce the observed line around 6550 Å.
- Radioactivity-powered Hα is too weak by 1-2 orders of magnitude.



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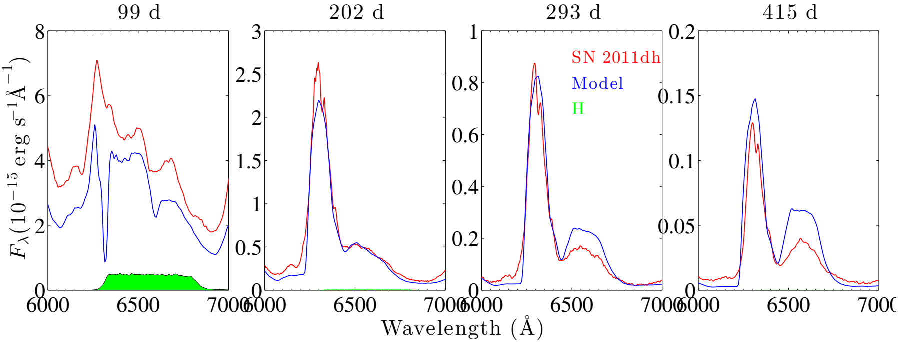
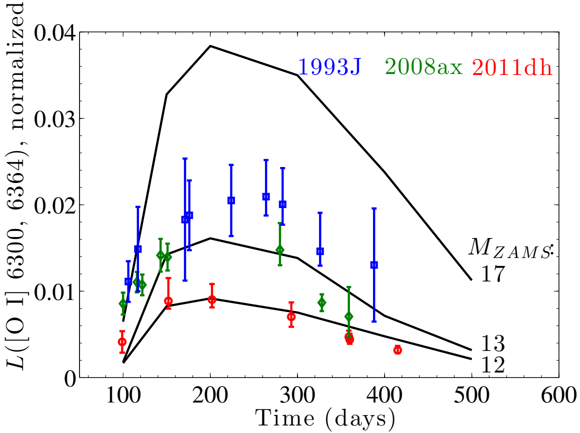


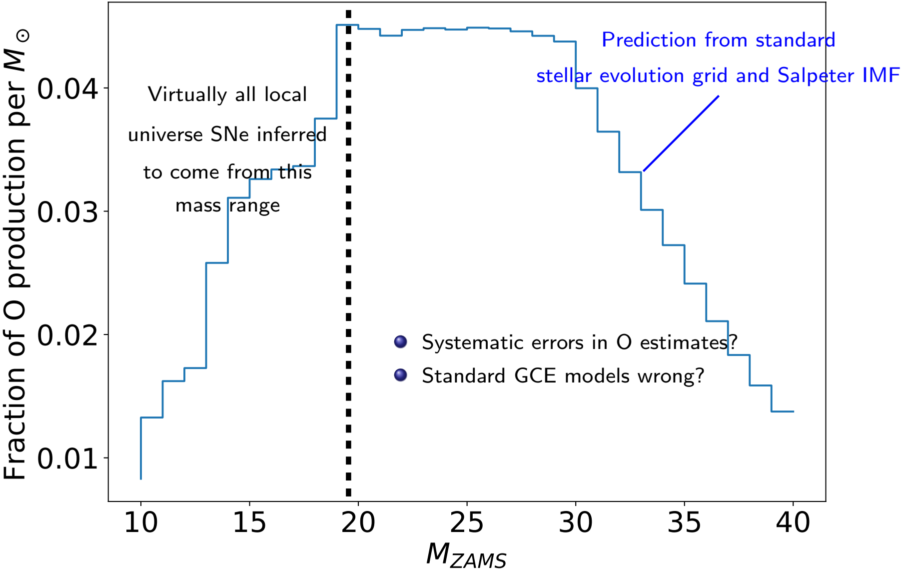
[O I] $\lambda\lambda$6300, 6364 in the three best observed IIb SNe → $M_{ZAMS} = 12 - 15\ M_\odot (M_O = 0.3 - 0.8 M\odot)$ → *low-mass stars stripped by binary interaction*

Picture holds in larger samples of Ib/IIb SNe (work in prep.)



AJ+2015, A&A

Which stars make most of our oxygen?



- Systematic errors in O estimates?
- Standard GCE models wrong?

Type Ic SNe (no H or He)

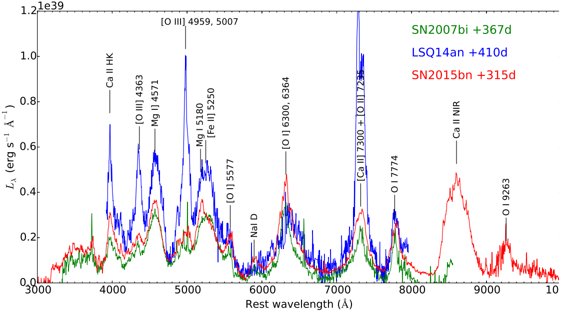
Most work so far single-zone modelling

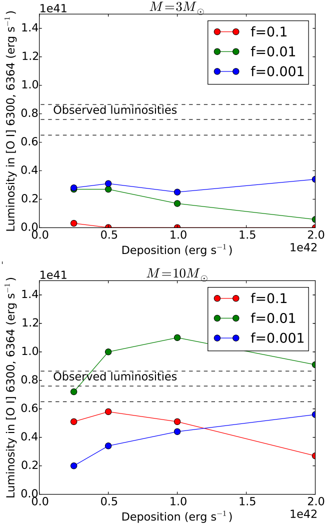
SN	$M(O)$	Reference
1997ef	0.5	Mazzali+2004
1997dq	0.8	Mazzali+2004
1998bw	3-5	Mazzali+2001
2002ap	1.2	Mazzali+2007b
2006aj	1.5	Mazzali+2007a
2007gr	0.8	Mazzali+2010
2009bb	1.1	Pignata+2011
2012ap	0.5	Milisavljevic+2015
PTF10qts	0.7	Walker+2014

Except for SN 1998bw, low/moderate amounts of nucleosynthesis, also $M_{ZAMS} \lesssim 20 M_{\odot}$ progenitors

SLSNe Ic shows the highest O masses inferred so far in any SN ($\gtrsim 5\ M_\odot$). This means *some* massive stars do explode

Jerkstrand+2017,ApJ

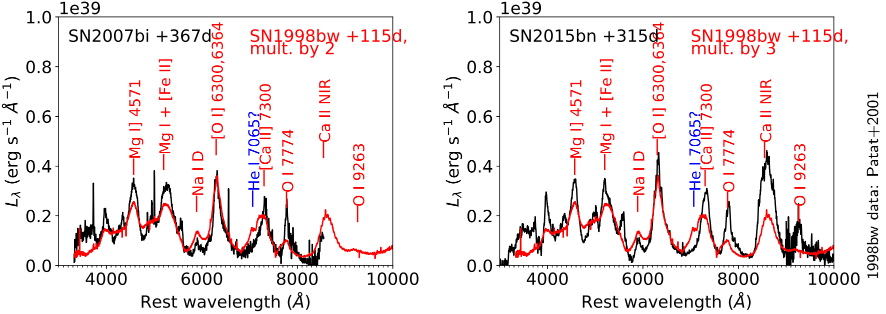




- Low O masses excluded by fundamental conflicts between powering levels and ionization state.
- Too rare to be significant galactic element producers.

f=volume filling factor

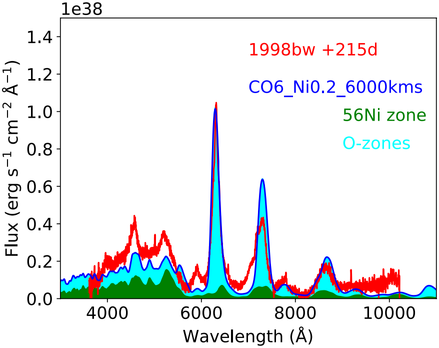
Strong similarity to GRB SNe such as SN 1998bw

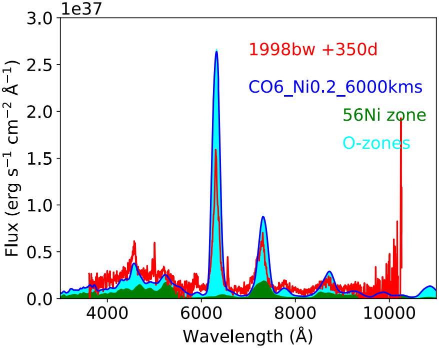


- Unlikely to involve fundamentally different scenarios.
- Is 4000-5500 Å plateau due to large amounts of Fe and therefore evidence for ^{56}Ni?

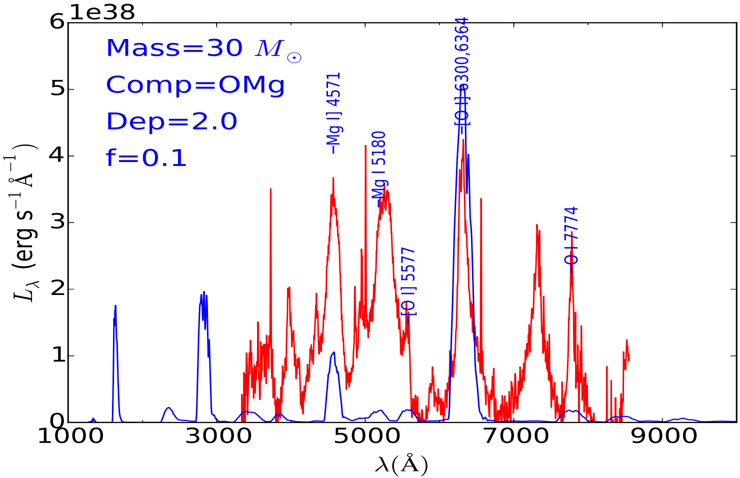
Understanding SN 1998bw *Jerkstrand+, in prep.*

- Standard ^{56}Ni-powered models powering 6-10 $M_\odot$ CO cores fit quite well.
- λ <5500 Å region formed by complex radiative transfer effects



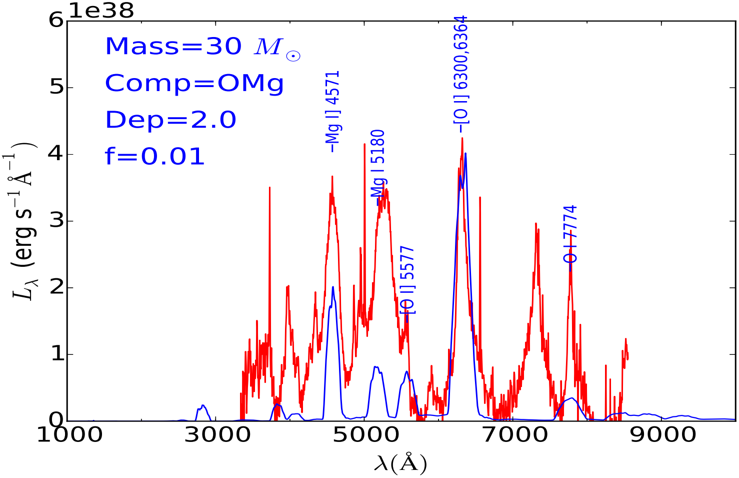


Superluminous Ic SNe : indications of clumping



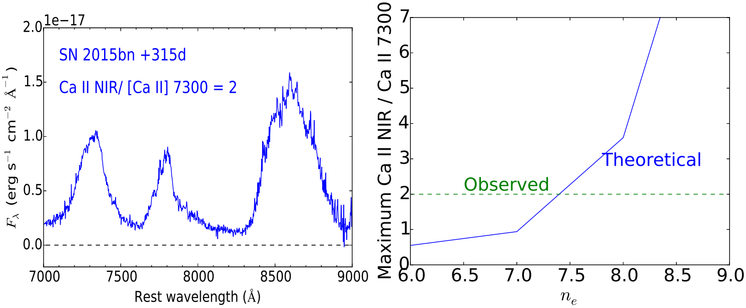
- High Mg I] 4571 luminosity requires cooling emission.
- Too large f : Mg fully ionized to Mg II $\rightarrow$ weak Mg I] 4571 cooling.

Superluminous Ic SNe : indications of clumping



- Decrease f : Mg I fraction increases → Mg I] 4571 strengthens and Mg I 5180 emerges.
- O I recombination lines strengthen, and can get also cooling contribution.

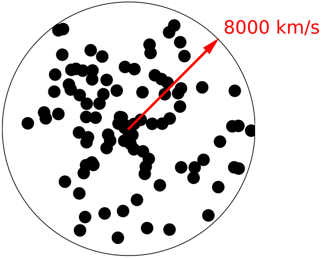
Superluminous Ic SNe : indications of clumping

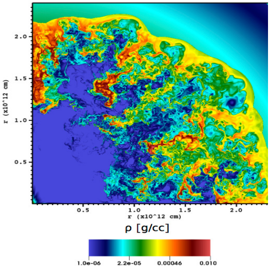


- Observed ratio requires high electron density, $n_e \gtrsim 10^8$ cm^{-3}.
- Similar result from O I recombination lines ($n_e = 10^8 - 10^9$ cm^{-3})
- Need low filling factor to make reasonable ejecta masses from those n_e:

$$M = 3000\ M_\odot f \left(\frac{n_e}{10^8\ \mathrm{cm}^{-3}}\right) \left(\frac{\bar{A}}{40}\right) \left(\frac{x_e}{0.1}\right)^{-1}$$

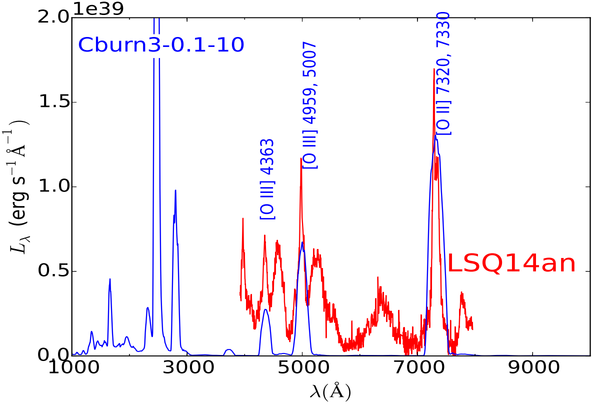
Magnetar-powered ejecta become clumped, but constraints not yet strong enough to rule out other scenarios





Chen+2016

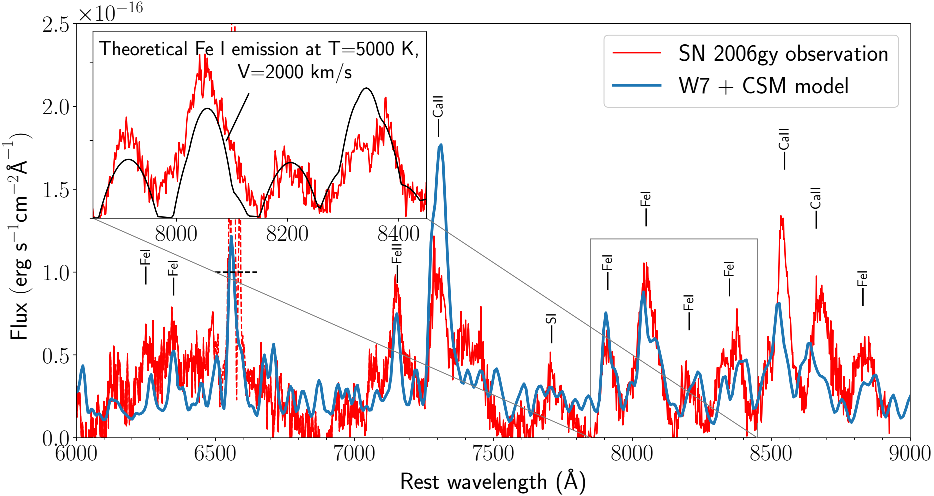
The O II and O III lines: evidence for a second ejecta component?



- Seen sometimes. Velocities lower than neutral lines.
- Need large energy deposition into a low mass/low density region to reproduce.
- Inner pulsar wind nebula? Circumstellar interaction component?

SN 2006gy - one of the brightest SNe ever seen - the result of a merger of a white dwarf with a massive star?

Jerkstrand, Maeda & Kawabata, Science 2020



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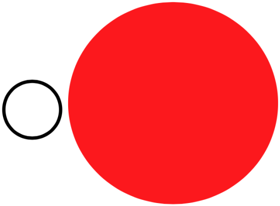
Jerkstrand, Maeda & Kawabata, Science 2020

- **Causally connects the massive CSM ejection and the SN** (inspiral $\rightarrow$ common envelope ejection followed by explosion when WD reaches the centre of the other star).
- **Common envelope ejection a well established process** - entire stellar envelope expected to be ejected on timescales of years/decades.
- **Ia SNe make the right amounts of ^{56}Ni** ($0.3 - 0.7\ M_\odot$).



Summary

- Analysis of supernova nucleosynthesis can be made by nebular-phase spectral modelling : SUMO is a state-of-the-art code used for this.
- Almost all (non-superluminous) stripped-envelope SNe show small/moderate amounts of nucleosynthesis and appear to originate from $M_{ZAMS} \sim 8 - 20\ M_{\odot}$ stars stripped in binaries.
- Some previous mysteries have probably been resolved - e.g. apparent Hα is in fact [N II] 6548, 6583 according to the models.
- Superluminous Ic SNe have higher O yields and could come from single stars (WR stars). Ejecta appear highly clumped.
- New detailed modelling of SN 1998bw ongoing.
- A recent breakthrough on SN 2006gy : nebular iron lines indicate a thermonuclear (Ia) supernova exploding inside an ejected common envelope